Density dependence of resonance broadening and shadowing effects in nuclear photoabsorption

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Abstract

Medium effects as a function of the mass number A are studied in the total photonuclear cross section from the Δ-resonance region up to the region where shadowing effects are known to exist. A consistent picture is obtained by simply assuming a density dependence of the different mechanisms of resonance broadening and shadowing. The Δ-mass shift is found to increase with A.

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The total photoabsorption cross section on nuclei has been recently measured at Frascati (see ref. [1, 2] and references therein) and Mainz [3] over the energy range 200-1200 MeV. A rather universal result is obtained for a variety of nuclei indicating a basically incoherent volume photoabsorption mechanism. In the region up to 500 MeV, the cross section per nucleon is not much affected by medium effects; the Δ peak due to the $P_{33}(1232)$ resonance is clearly evident and not much distorted in comparison with the free nucleon. In the region above 500 MeV, on the contrary, a strong damping and flattening of the cross section are observed so that the $D_{13}(1520)$ and the $F_{15}(1680)$ resonances, which are known to give the major contribution to the second and third peak of the free nucleon cross section, completely disappear even in light nuclei. Possible mechanisms responsible for such a distortion of the baryon resonances in the nuclear medium have been discussed [4]-[6], the major candidates being the Fermi motion, the Pauli blocking and the collision broadening due to the propagation of resonances inside nuclear matter.

Beyond 2 GeV the observed reduction of the absolute value of the nuclear photoabsorption cross section with respect to the free nucleon case might be related to the onset of shadowing effects [7] which are known to exist at higher energies on the basis of rather old data [8]. Consistency of resonance broadening and shadowing effects in the nuclear photoabsorption process in the whole range of energies from the Δ peak up to the shadowing region has been recently shown within a generalized photonuclear sum-rule approach [9]. In this letter we focus on the density dependence of the nuclear photoabsorption process.

Following the approach of ref. [6], in order to isolate the medium effects in the resonance region, the resonance mass M_0 and width Γ_0 for the free case have been taken from the fit of the nucleon photoabsorption cross section. Proton and neutron cross sections have been considered separately as a sum of a smooth background plus eight Breit-Wigner resonances ($P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, $D_{15}(1675)$, $F_{15}(1680)$, $D_{33}(1700)$, $F_{37}(1950)$), which are believed to give the main contribution to the total γN cross section below 1.2 GeV. The total nuclear photoabsorption cross section is given in terms of the imaginary part of the forward Compton scattering amplitude $\overline{\mathcal{T}}(\omega, \theta = 0)$ as

$$\frac{\sigma_{\gamma A}}{A} = -\frac{1}{2m\omega} \operatorname{Im} \overline{\mathcal{T}}(\omega, \theta = 0), \tag{1}$$

where ω is the photon energy, m is the nucleon mass and $\overline{\mathcal{I}} = \sum_i [(Z/A)\,\overline{\mathcal{I}}_{i,\gamma p} + (N/A)\,\overline{\mathcal{I}}_{i,\gamma n}]$. The elementary amplitude is given by a convolution over the nucleon momentum distribution $|\phi(\vec{p})|^2$ as

$$\overline{\mathcal{I}}_{\gamma N}(\omega, \theta = 0) = \int \frac{\mathrm{d}\vec{p}}{(2\pi)^3}\, \frac{|\phi(\vec{p})|^2 g^2_{\gamma N N^*}}{[(\vec{p} + \vec{k})^2 - M^2 + \mathrm{i}M\Gamma]}, \tag{2}$$

where $k = (\omega, \vec{k})$ and $p = (E, \vec{p})$ are the photon and nucleon four-momenta, and $g_{\gamma NN^*}$ is the vertex function for the $\gamma N \to N^*$ process. The effects of the medium are contained in the mass shift δM ($M = M_0 + \delta M$) and in the width Γ,

$$\Gamma = \frac{\Gamma_0 B_P + \Gamma^*}{S_F}, \tag{3}$$

where B_P is the Pauli blocking factor, S_F the Fermi suppression factor and Γ^* the broadening due to collisions and interactions. The Pauli blocking factor takes into account the increased lifetime of the resonance due to the other nucleons occupying the momentum space below the Fermi momentum p_F. The Fermi suppression factor S_F is a decreasing function of $x = 2\omega p_F / M\Gamma_0$. As x increases with ω, it is evident that the $\Delta(1232)$ is less affected by Fermi motion than the other resonances. Γ^* and δM measure the broadening of the resonance due to the interaction with surrounding nucleons; in the optical pseudopotential approach, δM and Γ^* are proportional to the real and imaginary part of the forward NN^* scattering amplitude $f_{NN^*}(0)$, respectively.

A similar fit to the photofission cross section has already been carried out for ^{238}U in ref. [6], where the total number of parameters were reduced to 5 by assuming $\delta M = 0$ for all resonances except for the Δ and a fixed broadening Γ^* of $P_{11}(1440)$, $S_{11}(1535)$, $D_{15}(1675)$, $F_{37}(1950)$. In fact these parameters do not contribute significantly to the χ^2.

In order to investigate medium effects we have introduced a density dependence in all these parameters adjusting the number A of nucleons, the nuclear density ρ and the Fermi momentum to the individual target nuclei. Representative nuclei such as ^{12}C, ^{63}Cu and ^{208}Pb were considered.

Using the optical theorem, the broadening Γ^* can be written as:

$$\Gamma^* = \rho\sigma^* \upsilon\gamma, \tag{4}$$

where σ^* is the total cross section for the NN^* interaction, γ is the Lorentz factor and v the propagation velocity ($\sigma^* v$= 40 mb). The product $l = v\gamma$ gives the mean free path of the resonance inside the nucleus. A constant $\rho = \rho_0$ has been assumed, where ρ_0 is the normalization constant of the usual Woods-Saxon form for $\rho(r)$.

The Fermi suppression factor and the Pauli blocking factor also depend on the nucleus through p_F, which is 0.221 GeV for ^{12}C, 0.240 GeV for ^{64}Cu and 0.265 GeV for ^{208}Pb.

Finally, some dependence of the mass shift δM of the Δ on the number of nucleons has to be expected, as already found in electron scattering [10].

The results are shown in Fig. 1. While heavier nuclei keep no trace of the second and third peak of the free-nucleon cross section, in the case of ^{12}C it is possible to see a little broad bump corresponding to the second free-nucleon peak in both the theoretical curve and the data. On the other hand, the Δ peak is well pronounced and the less affected by collision broadening. However, it is clear that also the Δ peak is damped for heavier nuclei, as an effect due to the medium density. In agreement with data, the area under the resonance curve is unchanged, but the width increases with A. For ^{12}C we have $\Gamma^* = 51$ MeV for the Δ, while it is between 218 MeV and 235 MeV for the other resonances ($D_{13}(1520)$, $F_{15}(1680)$, $D_{33}(1700)$). Similarly, $\Gamma^* = 67$ MeV for the Δ and between 280 MeV and 305 MeV for the other resonances in the case of ^{63}Cu and $\Gamma^* = 74$ MeV for the Δ and between 315 MeV and 340 MeV for the others in the case of ^{208}Pb. Moreover, the Δ-mass shift δM shows a slight dependence on A. Data on ^{12}C are well described by $\delta M = 12$ MeV, while $\delta M = 15$ MeV for ^{63}Cu and $\delta M = 18$ MeV for ^{208}Pb. These values are comparable with those extracted in ref. [2] from experimental data, which can be interpolated by a curve linearly dependent on A.

Anyway, it is possible to say that $\sigma_{\gamma A}/A$ does not strongly depend on A in the resonance region. On the contrary, in the range of energies between 2 GeV and 20 GeV, shadowing effects have been observed in the photonuclear cross section. These effects introduce a correction to the cross section which can be expressed in terms of an effective number of nucleons, A_{eff}, as

$$\sigma_{\gamma A}(\omega) = A\sigma_{\gamma N} - \Delta\sigma = A_{\text{eff}}(\omega)\sigma_{\gamma N}. \tag{5}$$

As discussed in many papers (see, e.g., [7, 8, 11]), in the region above 1 GeV diffractively produced intermediate hadronic states occur by analogy

with the case of hadron scattering by nuclei. The main contribution comes from the lightest vector mesons, ρ, ω and ϕ (the ρ-production threshold is 1.08 GeV).

In the eikonal approximation the Green function for the vector meson V propagating from $\vec{r} = (\vec{b}, z)$ to $\vec{r}\,' = (\vec{b}\,', z')$ with momenutm $\vec{k}_V$ can be written in the form [9]

$$G_V(\vec{b}\,', z'; \vec{b}, z) = \frac{1}{2\mathrm{i}k_V} \exp\left\{ \mathrm{i} \int_z^{z'} \mathrm{d}\xi \left[k_V + \frac{2\pi}{k_V} f_V(0) \rho(\vec{b}, \xi) \right] \right\} \delta(\vec{b} - \vec{b}\,')\, \theta(z - z'), \tag{6}$$

where $\vec{b}$ is the impact parameter, $f_V(0)$ is the forward VN scattering amplitude and the z axis is taken along the resonance momentum $\vec{k}$.

Using this Green function we can easily find the shadowing correction as

$$\Delta\sigma = \frac{4\pi}{k} \operatorname{Im} F_{\gamma\gamma}^{(2)}, \tag{7}$$

where

$$F_{\gamma\gamma}^{(2)} = -4\pi \sum_V \int \mathrm{d}\vec{r} \int \mathrm{d}\vec{r}\,' \, \mathrm{e}^{-\mathrm{i}\vec{k}\cdot\vec{r}\,'} f_{\gamma V}(0) \rho_2(\vec{r}, \vec{r}\,') G_V(\vec{r}\,', \vec{r})\, f_{V\gamma}(0)\, \mathrm{e}^{\mathrm{i}\vec{k}\cdot\vec{r}}, \tag{8}$$

with $f_{\gamma V}(0)$ being the forward γV transition amplitude. In eq. (8) $\rho(\vec{r}, \vec{r}\,')$ is the two-body density function. In the case of an uncorrelated system, the usual approximation of ρ_2 in terms of one-body densities, i.e. $\rho_2(\vec{r}, \vec{r}\,') = \rho(\vec{r})\rho(\vec{r}\,')$ makes the above formulae to be equivalent to the optical-model approximation to the multiple scattering expansion used in ref. [8].

We incorporate correlations between pairs of nucleons choosing the simple Bessel function parametrization for the two-body correlation function

$$\Delta(\vec{r}, \vec{r}\,') = \rho_2(\vec{r}, \vec{r}\,') - \rho(\vec{r})\rho(\vec{r}\,') = -j_0(q_c|\vec{r} - \vec{r}\,'|)\rho(\vec{r})\rho(\vec{r}\,'), \tag{9}$$

where $q_c = 780$ MeV [12].

The results shown in Fig. 2 have been obtained with the parametrization of the $f_{\gamma V}$ amplitudes in model I of ref. [8] putting however the real parts of the forward scattering amplitudes $f_{\gamma V}(0)$ equal to 0. A rather satisfactory agreement with data is gained, especially when including correlations whose

contribution to $A_{\rm eff}/A$ is about 10% for copper and lead and about 5% for carbon. $A_{\rm eff}/A$ decreases with energy towards an asymptotic constant value in agreement with the finding of ref. [7], i.e.

$$A_{\rm eff}/A = A^{-0.09}. \tag{10}$$

According to our calculations this constant value is reached more rapidly for lighter nuclei, already above 6 GeV for carbon. This is also the trend of the available data. However, better data are certainly welcome to test the density dependence of the shadowing effects.

Taking into account correlations, there is a region of energies (below 2 GeV) where $A_{\rm eff}/A > 1$, i.e. antishadowing takes place. This was also found in the case of ^{238}U [9] and happens because correlations essentially change the dependence of the amplitude $F^{(2)}_{\gamma\gamma}$ on the longitudinal momentum transfer $q_L = k - k_V = \omega - \sqrt{\omega^2 - m_V^2}$ in the region where $q_L r > 1$. No data exist in this energy region which is the typical range of energies explored at CEBAF [15] and ELSA [16]. Therefore we hope that new data will help to understand the onset of shadowing.

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Figure captions

Fig. 1. The total photoabsorption cross section for ^{12}C, ^{63}Cu and ^{208}Pb. Data from [2].

Fig. 2. Results of calculations of $A_{\rm eff}/A$ for ^{12}C, ^{63}Cu and ^{208}Pb taking into account contributions of ρ, ω, and ϕ. The solid and dashed curves refer to calculations with and without correlations. The data are from SLAC [13] (circles) and Cornell [14] (triangles).